

Examples of unusual ionospheric observations made by the DEMETER satellite over seismic regions

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Abstract

The micro-satellite DEMETER was launched on June 29, 2004 in a polar and circular orbit with an altitude of ~710 km. It is a CNES mission controlled from Toulouse in France. The main objective of DEMETER is to search and characterize ionospheric perturbations that can be associated with the seismic activity in order to better understand the generation mechanism of such perturbations. Its scientific payload allows us to measure waves in a broad frequency range and also some important plasma parameters (ion composition, electron density and temperature, energetic particles). This paper is a preliminary report of unusual observations recorded by DEMETER over seismic regions prior to earthquakes. The main purpose of the project is to perform a statistical analysis with many events in order to determine the necessary conditions to observe such seismo-electromagnetic effects. It is too early to perform such statistics but data recorded during selected events and shown here are useful since they may point out sensitive parameters which must be particularly surveyed in the statistical analysis.

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1. Introduction

The French micro-satellite DEMETER was launched on June 29, 2004 and one of its main scientific objectives is to detect anomalous variations of electromagnetic waves, particle fluxes or thermal plasma parameters which could be related to seismic activity. If it is shown that such perturbations are real and systematic, they could be considered as short-term precursors, occurring between a few hours and a few days before the quake. A huge number of papers have been already published on seismo-electromagnetic effects and disturbances of the neutral and ionized upper

atmosphere and their possible generation mechanisms. One can refer to the more recent ones: Hayakawa et al. (2004), Pulinets (2004), Pulinets and Boyarchuk (2004), Meloni et al. (2004), Tsai and Liu (2004) and references therein. Up to now, DEMETER is the only satellite which has the capability to survey on a vast scale the Earth's electromagnetic environment in the ionosphere. The data base which will be built during the mission will allow us to perform the statistical analysis which is necessary to ascertain the link of the recorded perturbations with the seismic activity.

At the present time, after a few months of operations, the aim of this paper is to show some examples of ionospheric perturbations which have been recorded by the various experiments onboard DEMETER when it was flying over active seismic regions. Section 2 will briefly describe

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the scientific payload of the satellite. Events will be shown in Section 3 and a short discussion is given in Section 4.

2. DEMETER

The orbit of DEMETER is polar and circular with an altitude of 710 km. The scientific payload of DEMETER is composed of several instruments which provide a nearly continuous survey of the plasma, waves and energetic particles. ICE, the electric field experiment, uses four electric probes to measure the three components of the electric field in a frequency range from DC up to 3.5 MHz. IMSC, a search-coil magnetometer, measures the three components of the magnetic field in a frequency range from a few Hz up to 20 kHz. ISL, the Langmuir probe gives access to the electron density and temperature. IAP, the thermal ion spectrometer measures the ion density, composition, temperature and flow velocity. A solid state energetic particle detector, IDP, measures high energy electrons and protons. Details about these experiments can be found in Berthelier et al. (2006a,b), Lebreton et al. (2006), Parrot et al. (2006), Sauvaud et al. (2006). There are two modes of operation: (i) a survey mode to record low bit rate data all around the Earth at invariant latitudes less than $\sim 65^\circ$, and (ii) a burst mode to record high bit rate data above seismic regions. The data are stored in a large onboard memory which is downloaded two times per day when the satellite is above Toulouse, the location of the Operation Center. Then, the data is sent to the DEMETER Mission Center in Orléans where various data treatments are done (Lagoutte et al., 2006). Data and plots are available through a web server (<http://demeter.cnrs-orleans.fr>). The quick-look plots are in public access. The seismic information is routinely merged with the orbitography of DEMETER and introduced in a data base in order to facilitate selection of events following various requirements (magnitude, depth, distance between the satellite and the epicentre, time interval between the time of the quake and the time of the data). Experimenters and guest investigators have access to these facilities in order to download or to display online selected data. All data files and plots are organised by half-orbits.

3. Events

Fig. 1 presents the ground track of the DEMETER orbit above Japan on August 29, 2004 seven days before a series of two earthquakes of magnitude 6.9 and 7.4 which occur on September 5, 2004 in the region of Kii-Peninsula (Geographic Lat = 33.05°N , Geographic Long = 136.78°E) at 10.07.07 UT and 14.57.18 UT, respectively. The corresponding data along this orbit are shown in Fig. 2. From the top to the bottom, the first panel shows a spectrogram of an electric component up to 2 kHz, and the second panel displays the spectrogram of a magnetic component in the same frequency range. The intensity of the emissions is colour coded according to the scale on the right. Regular

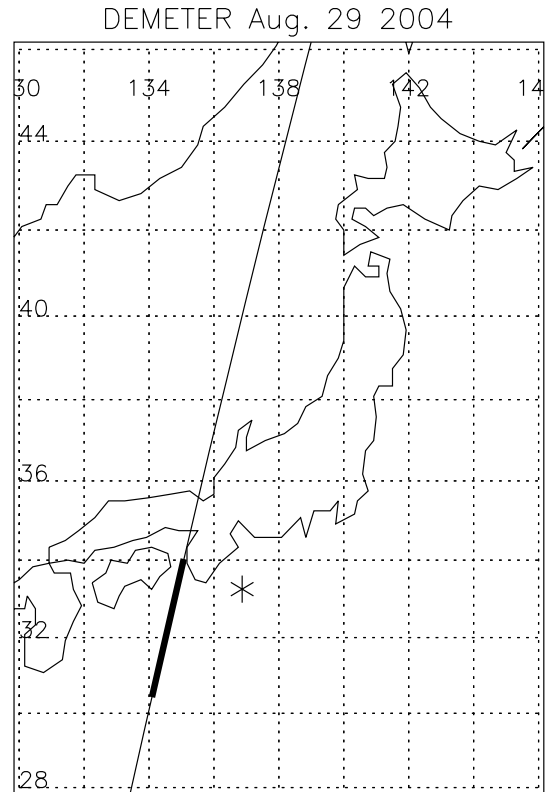


Fig. 1. Orbit of DEMETER above Japan on August 29, 2004. The star indicates the epicenter of a series of two earthquakes which occurs on September 5, 2004 in the region of Kii-Peninsula. The thick line on the orbit corresponds to the period where an ionospheric perturbation is observed with DEMETER (see text and Fig. 2).

pulses at 625 Hz observed on both spectrograms are due to the onboard calibrations. Two times on the magnetic spectrogram, high intensity interferences are seen lasting ~ 100 s. They are generated by the magneto-torquers operated to desaturate the reaction of wheels which are used for the attitude control. Ion densities are shown on the third panel and the electron density on the fourth panel. The last panel indicates the satellite closest approach of past and future earthquakes epicentres that are within 2000 km from the DEMETER orbit. The Y-axis represents the distances D between the epicenters and the satellite, from 750 km up to 2000 km. The symbols are filled green square for post-seismic events, filled red triangle for pre-seismic events, and filled blue circle for earthquakes occurring during the half-orbit. The color scale on the right represents the time interval between the earthquakes and the DEMETER orbit with a color gradation from >30 days up to a $[0-6 \text{ h}]$ interval. The empty symbols have similar significations except that they are related to the conjugate points of the epicentres (the distance D is then the distance between the conjugate points of the epicenters and the satellite). The symbol sizes correspond to earthquakes of magnitude $[5-6]$, $[6-7]$, and $[>7]$. In Fig. 2, the large red triangle at the bottom of the panel indicates the closest approach to the epicentre of an earthquake which will occur at 01:35:40 UT.

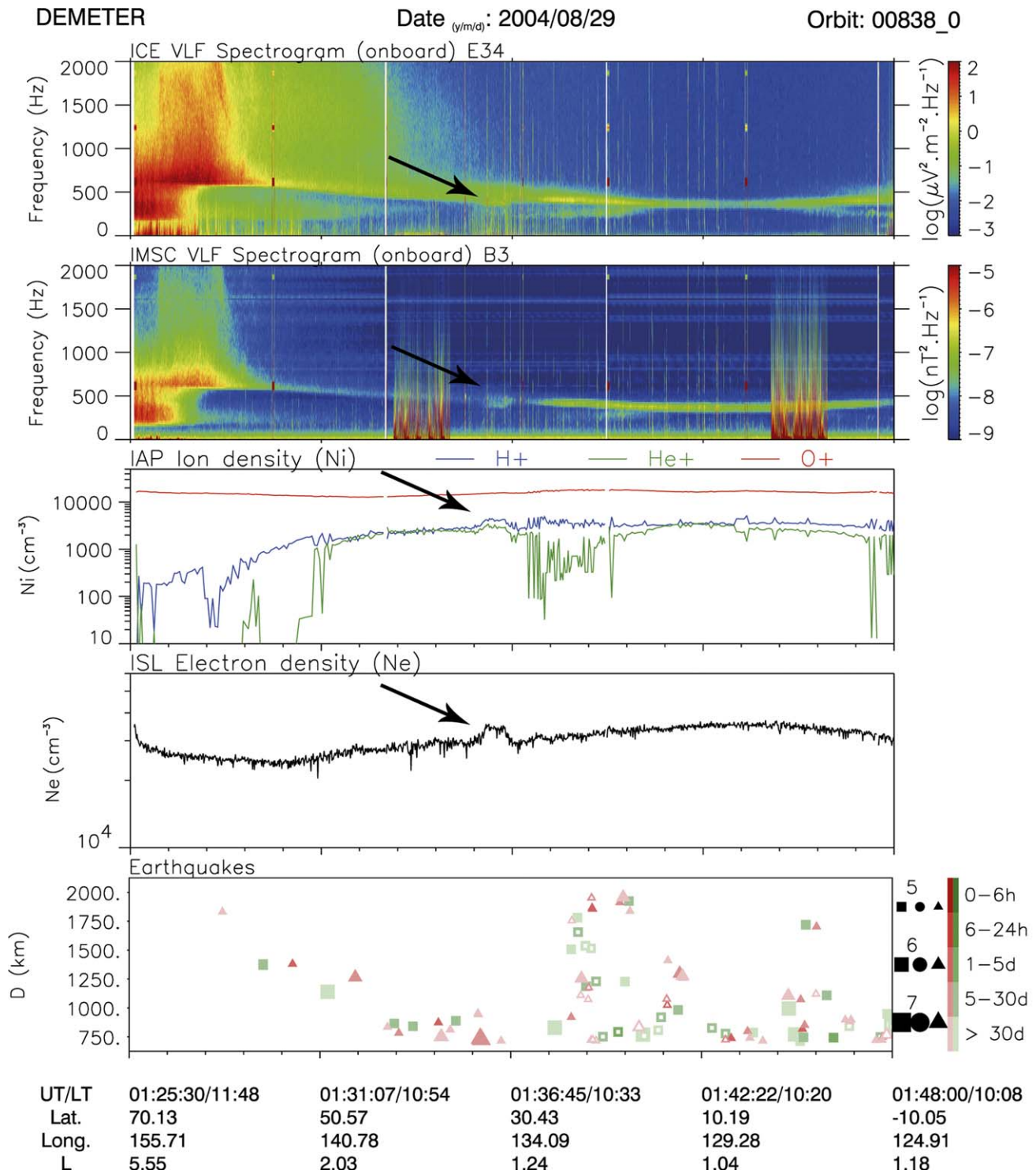


Fig. 2. From the top to the bottom the panels successively show a spectrogram of the electric component E34 between 0 and 2 kHz, a spectrogram of the magnetic component B3 between 0 and 2 kHz, the ion density given by IAP, the electron density, and the earthquakes seen by DEMETER along the orbit (see text for explanation). The data are presented as a function of the Universal Time (UT). The Local Time (LT), the geographic latitude and longitude, and the L values are also given.

Simultaneous disturbances are observed at this time by the four instruments. The cut-off frequency of the electromagnetic waves detected by ICE and IMSC decreases and simultaneously electrostatic turbulence can be

observed. A significant increase in the light ion densities and in the electron density can be noticed. It must be noticed that there is a discrepancy between the values of Ne and Ni (of the order of 30% at 01.36.11 UT) because

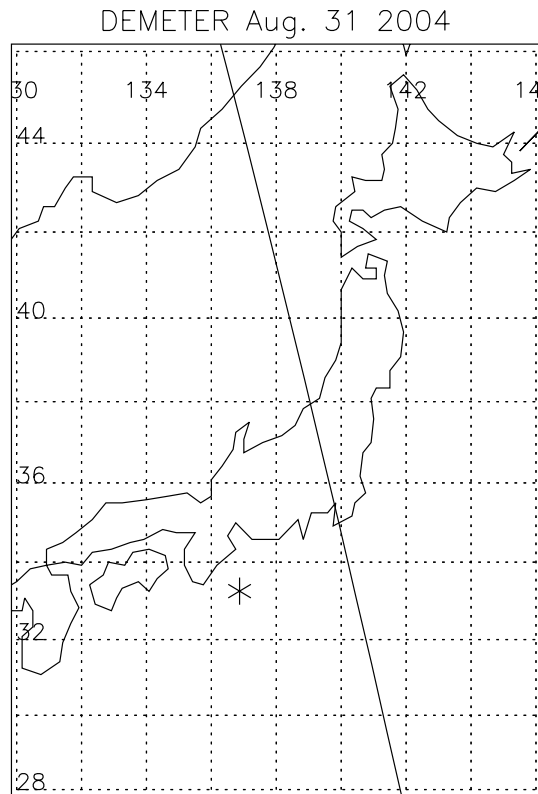


Fig. 3. For the same earthquake as in Fig. 1, another orbit above Japan on August 31, 2004.

the two different instruments (see Section 2) are not inter-calibrated, and only individual variations relative to each data set must be considered. The distance on which these variations are observed is shown by a thick line in Fig. 1.

Five days before the same earthquakes, DEMETER is flying again above this seismic region (Fig. 3) and the corresponding data are represented in Fig. 4. Relatively to Fig. 2, the data are now recorded during night time. The closest approach to the future epicentre is at 12:30:12 UT. At this time the cut-off frequency of the ELF hiss marks a sudden change.

A different observation was performed on January 21, 2005 along the orbit which is shown in Fig. 5. In this Figure the star indicates the position (1.22°S, 119.82°E) of an earthquake ($M = 6.2$) which occurs on January 23, 2005 at 20:10:11 UT. The data recorded by DEMETER two days and a half before are shown in Fig. 6. The first two panels represent the spectrograms of the magnetic component B2 and of the electric component E12 up to 2 kHz. The two thick vertical lines determine the time interval where the experiments are in burst mode. The bottom panel shows the position of the earthquake and it can be seen that the closest approach is at 02:16:45 UT. At this time, an electromagnetic emission at 130 Hz is observed on the electric and magnetic components, less visible on the magnetic one due to the low frequency noise. As these data are recorded in burst mode it is possible to determine

the propagation characteristics of this emission. The six components of the electromagnetic field are available and have been processed using the PRASSADCO code (Santolik, 2001) already used in a preliminary form to process data from the FREJA wave experiment (Santolik and Parrot, 1999) and specially designed to analyze the spectral matrix computed by the STAFF experiment onboard CLUSTER (see for example, Parrot et al., 2003; Santolik et al., 2003a). It has been adapted to process the DEMETER data transformed to a coordinate system linked to the earth's magnetic field B_0 . The results of the analysis are shown in Fig. 7.

The top panel gives a detailed spectrogram of the sum of the power-spectral densities in the three recorded electric components. The black line indicates the proton gyrofrequency. The following comments will focus on the wave which appears at ~ 130 Hz (below the proton gyrofrequency) between 02:16:00 and 02:17:00 UT. For analysis of waves at higher frequencies one can refer to studies performed with other satellites (see for example, Santolik and Parrot, 1999). The second panel represents the sense of polarization calculated following the Eq. (4) of Santolik et al. (2001). A value larger than +1 (red color)¹ corresponds to a right-hand polarization. The third and fourth panels give the polar θ and azimuthal ϕ angles of the wave normal direction in a frame of reference where the Z-axis is aligned with the earth's magnetic field B_0 . Both angles are calculated from the magnetic field components using the singular value decomposition (SVD) method (Santolik et al., 2003b). It can be seen that at 130 Hz the wave normal direction makes an angle of about $50^\circ \pm 10^\circ$ with B_0 . The last three panels display the estimation of the three components of the Poynting vector S_{\parallel} , S_x , and S_y . S_{\parallel} is the projection of the Poynting vector onto B_0 , and σS_{\parallel} is a normalisation factor which corresponds to the standard deviation of S_{\parallel} due to the spectral analysis. Data are recorded in the Southern hemisphere, and, according to the color scale, the red color of S_{\parallel} shows that the wave propagates along the direction of B_0 , i.e. it is an upgoing wave coming from a region below the satellite. This event was studied in more details by Santolik et al. (2006) who performed a backward ray tracing up to 300 km which indicates that this wave at 130 Hz may issue from the ionosphere. The red color of S_x indicates that the wave is propagating towards larger L -values. The behaviour of the other waves observed below the proton gyrofrequency is similar to events shown in Santolik and Parrot (1999), Santolik et al. (2006).

Our last example will describe an observation performed by the energetic particle experiment IDP. It is related to an earthquake of magnitude 7.3 which occurred on November 22, 2004 at 20:26:25 UT close to New Zealand (46.57°S, 164.83°E). Two DEMETER orbits are very close to this

¹ For interpretation of color in Fig. 7, the reader is referred to the web version of this article.

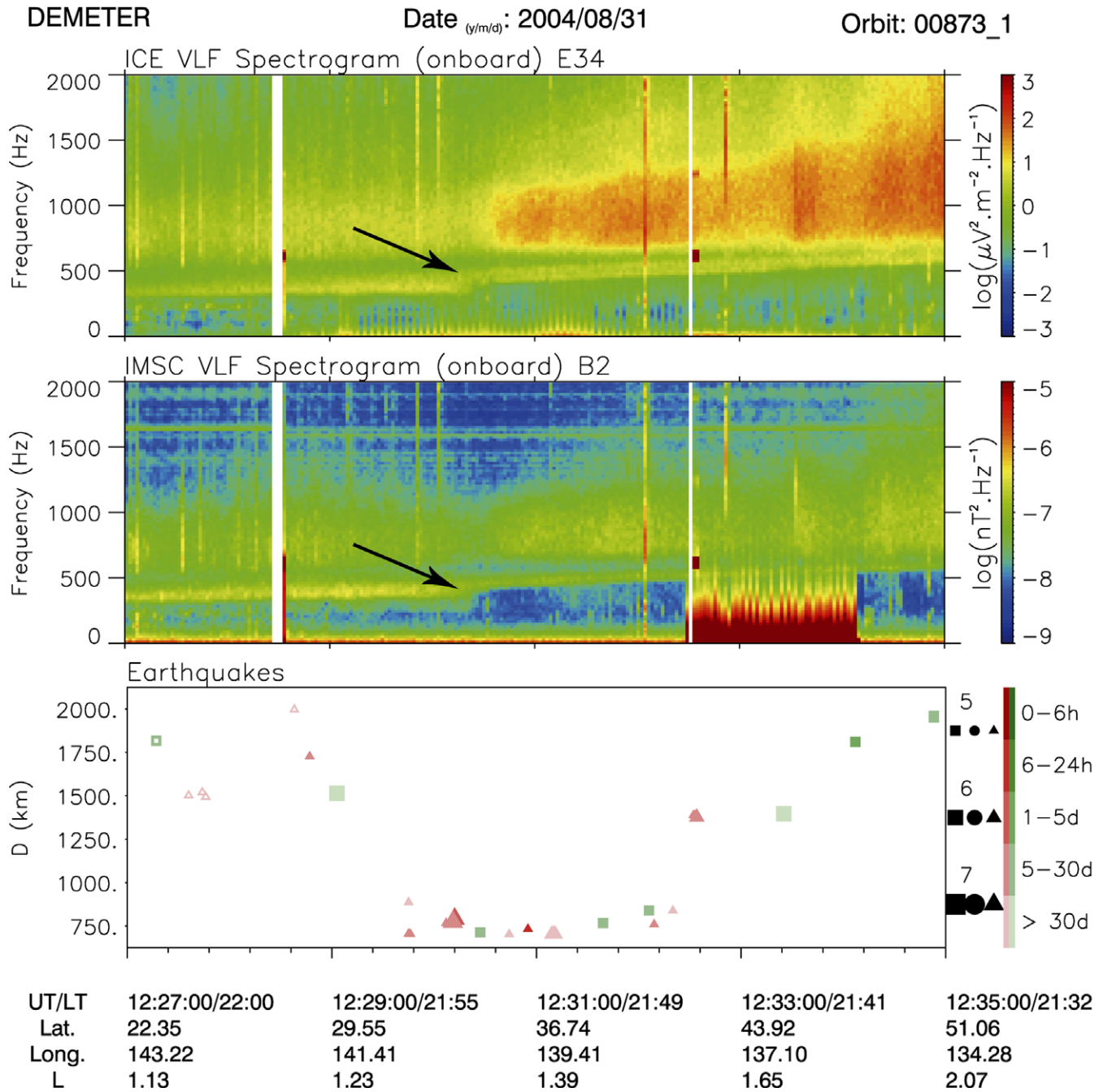


Fig. 4. From the top to the bottom the panels successively show a spectrogram of the electric component E34 between 0 and 2 kHz, a spectrogram of the magnetic component B3 between 0 and 2 kHz, and the earthquakes seen by DEMETER along the orbit. The data are presented as a function of the Universal Time (UT). The Local Time (LT), the geographic latitude and longitude, and the L values are also given.

earthquake. They are shown in Figs. 8 and 10 and the corresponding data recorded respectively two days and one day before the earthquake are displayed in Fig. 9 and Fig. 11. The presentation of Figs. 9 and 11 are similar. The two first panels show spectrograms of the magnetic component B2 and the electric component E12. The third panel represents the energy spectrogram of the electrons up to 2352 keV. The bottom panel provides information on the positions of earthquakes observed along the orbit. In Fig. 9, it is shown that the closest approach to the earth-

quake is at 12:16:15 UT. The data are recorded during night time. Just above the future earthquake there is an increase of the particle flux and very shortly after one can observe a burst of electrostatic turbulence. The electrostatic turbulence which is in fact observed since 12.13.40 UT decreases at the time of the particle flux enhancement and increase after. As we are at high latitude this turbulence may be due to auroral processes because the magnetic activity is moderate (K_p is between 3 and 4). In Fig. 11, the closest approach to the earthquake is at 22:32:20 UT and

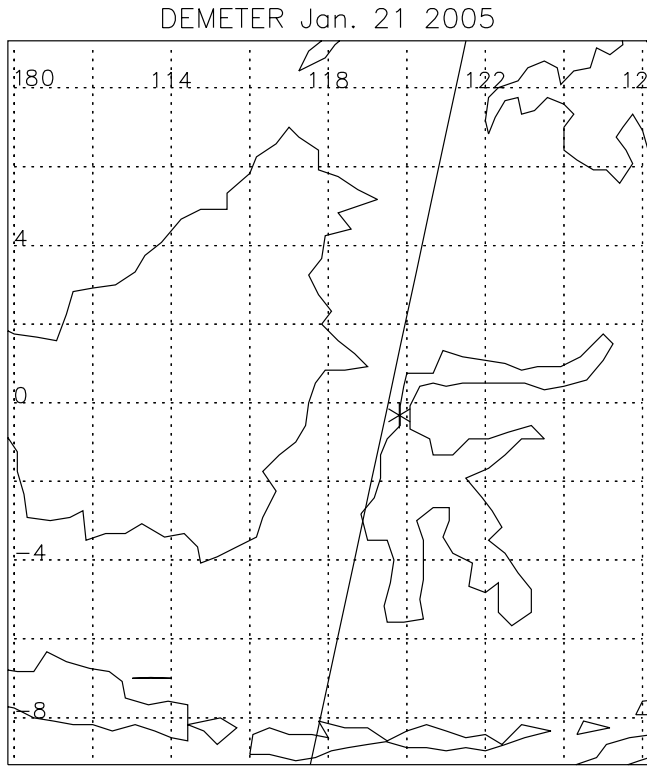


Fig. 5. Track of the DEMETER orbit on January 21, 2005 when the satellite is above Indonesia. The star indicates the position of an earthquake which occurs on January 23, 2005.

the data are recorded during day time. Oppositely to the event shown before, which is recorded during night time, a decrease of the particle flux is now observed above the seismic zone. At the same time, the spectrogram of the electric component E12 displays electrostatic turbulence.

4. Discussion

We have shown in this paper, examples of quite unusual features in waves, plasma or energetic particle fluxes recorded when the satellite was flying over epicenters of future earthquakes. These examples have been automatically selected by a tool of the DEMETER mission center (Lagoutte et al., 2006) which sorts out satellite orbits at a selected distance to epicenters of earthquakes with a magnitude larger than 6. These events were observed close to the location of epicenters of future earthquakes and therefore are interesting in the sense that they may represent the visible part of phenomena associated with an on-going seismic activity before the quake itself. However one has to keep in mind that all the measured parameters also display variations in absence of seismic activity since the mid-latitude ionosphere is affected by a number of other sources of perturbations and primarily by auroral activity. Therefore, it is now necessary to tackle the problem at the other end. Similar perturbations must be systematically searched on the complete data base in order to determine whether some

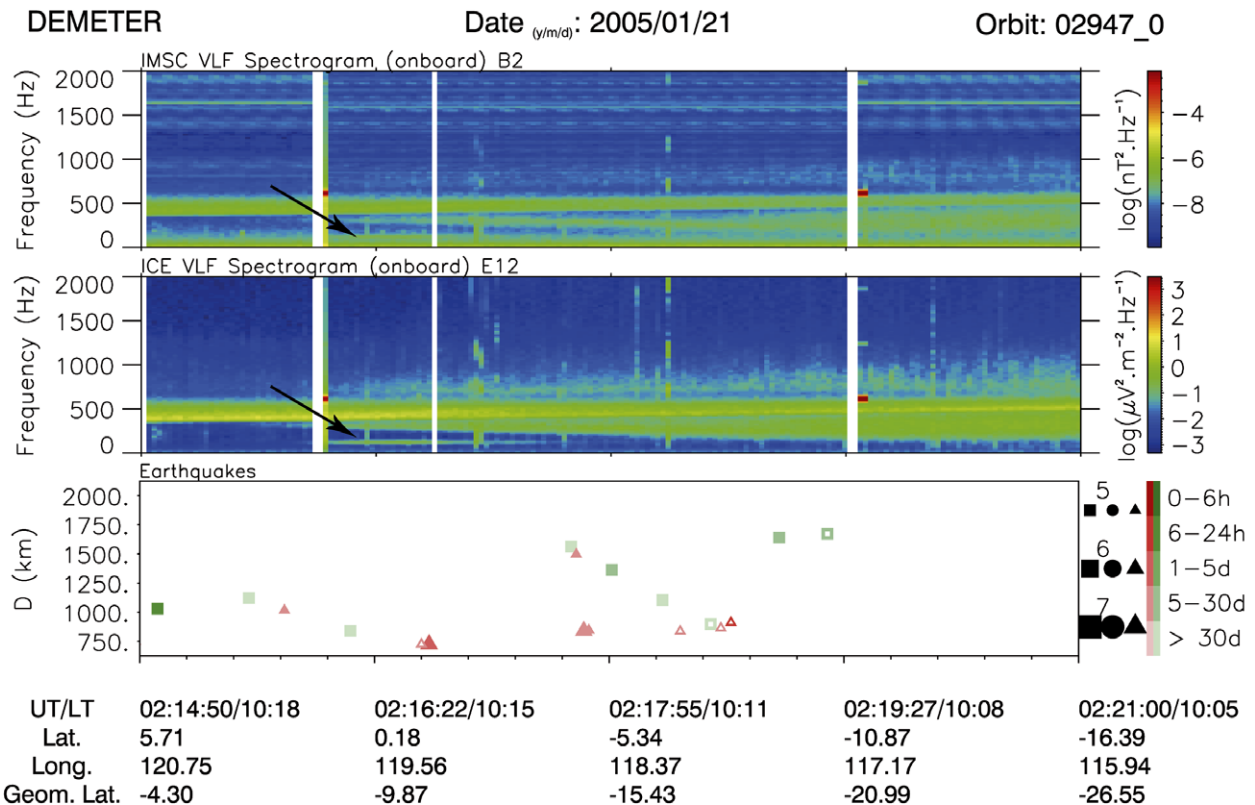


Fig. 6. Data recorded by DEMETER along the orbit shown in Fig. 5. The top panel is related to a magnetic spectrogram, the middle panel to an electric spectrogram, and the bottom panel to the earthquakes “seen” by the satellite. At the bottom, UT, LT, geographic latitude and longitude, and geomagnetic latitude are indicated.

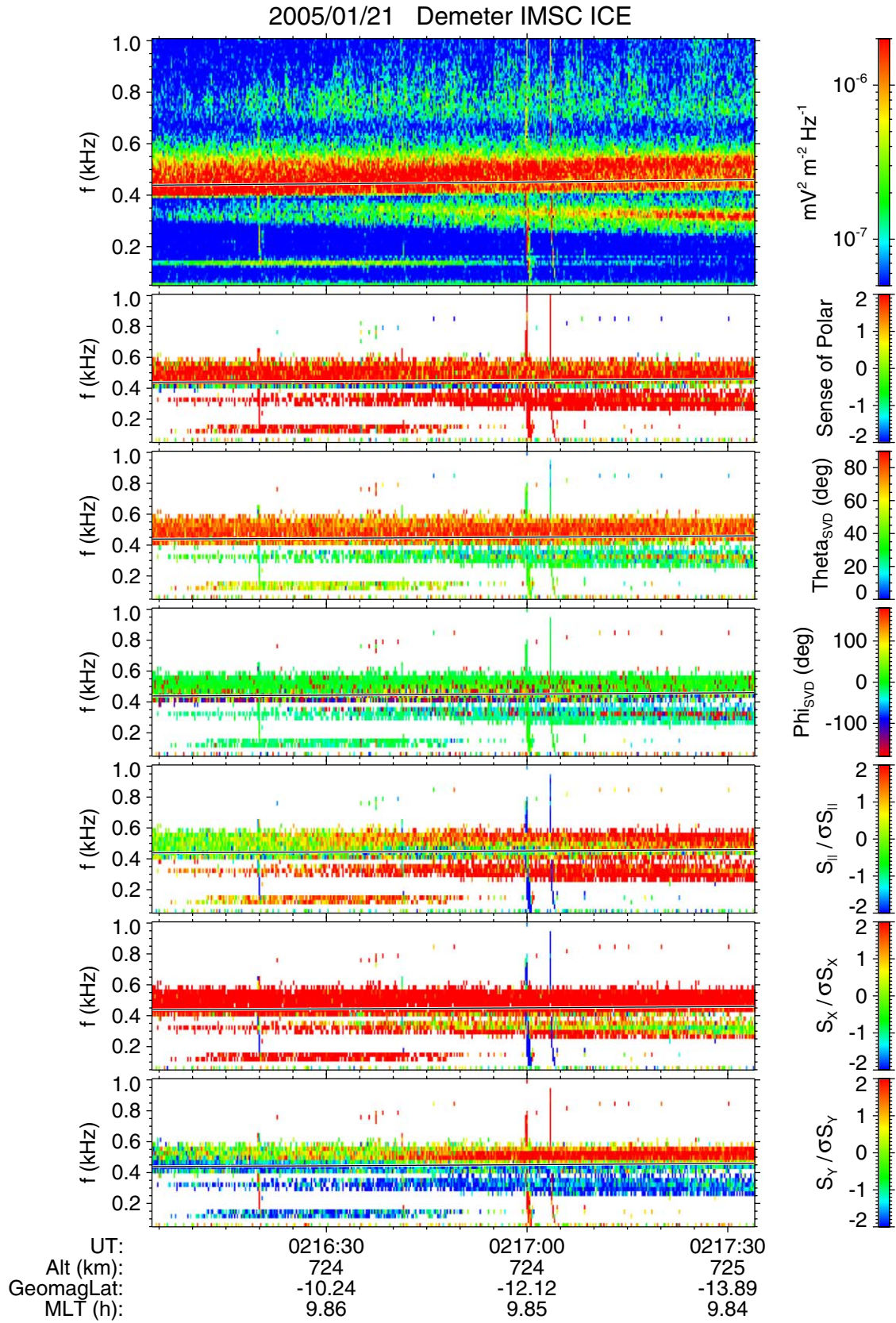


Fig. 7. Wave analysis of the event shown in Fig. 6. From top to bottom, detailed spectrogram of one electric component, sense of polarization, polar and azimuthal angles of the wave vector with the earth's magnetic field B_0 , projections of the Poynting vector onto the three axis of the frame of reference (see text for explanation). The geophysical parameters at the bottom are the Universal Time (UT), the altitude, the geomagnetic latitude, and the Magnetic Local Time (MLT).

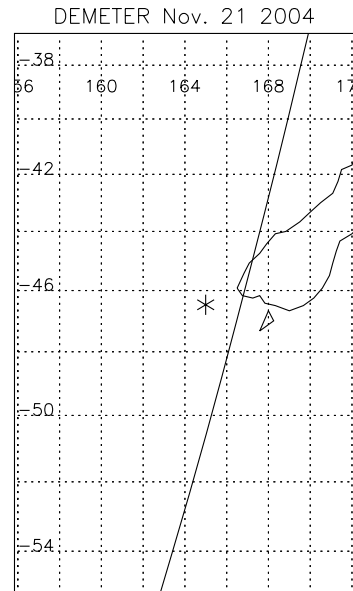
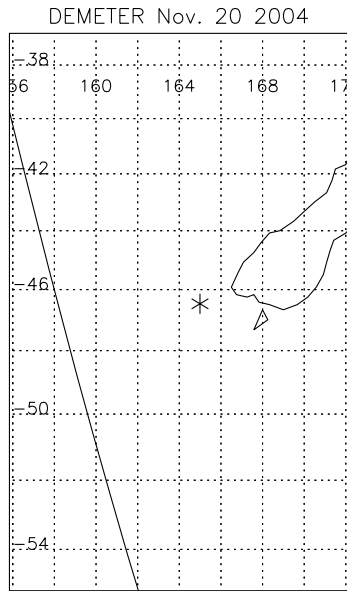


Fig. 8. Track of the DEMETER orbit on November 20, 2004 close to New Zealand. The star indicates the position of an earthquake which occurs on November 22, 2004.

Fig. 10. A track of the DEMETER orbit on November 21, 2004 close to the same earthquake as in Fig. 8.

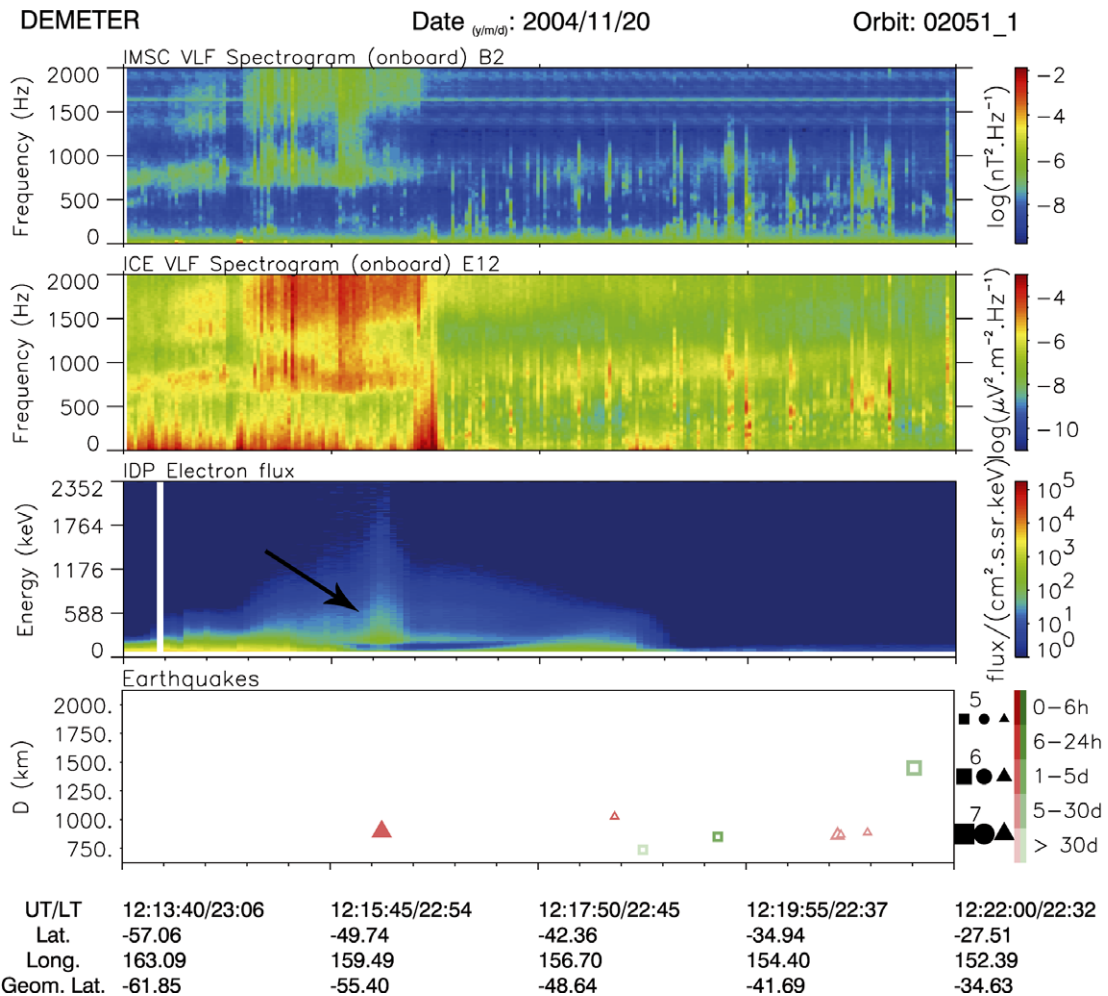


Fig. 9. From the top to the bottom, spectrogram of a magnetic component, spectrogram of an electric component, spectrogram of the energy flux of particles, and positions of the earthquakes along the orbit which is shown in Fig. 8. The data is recorded two days before the earthquake indicated by a bright red triangle. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

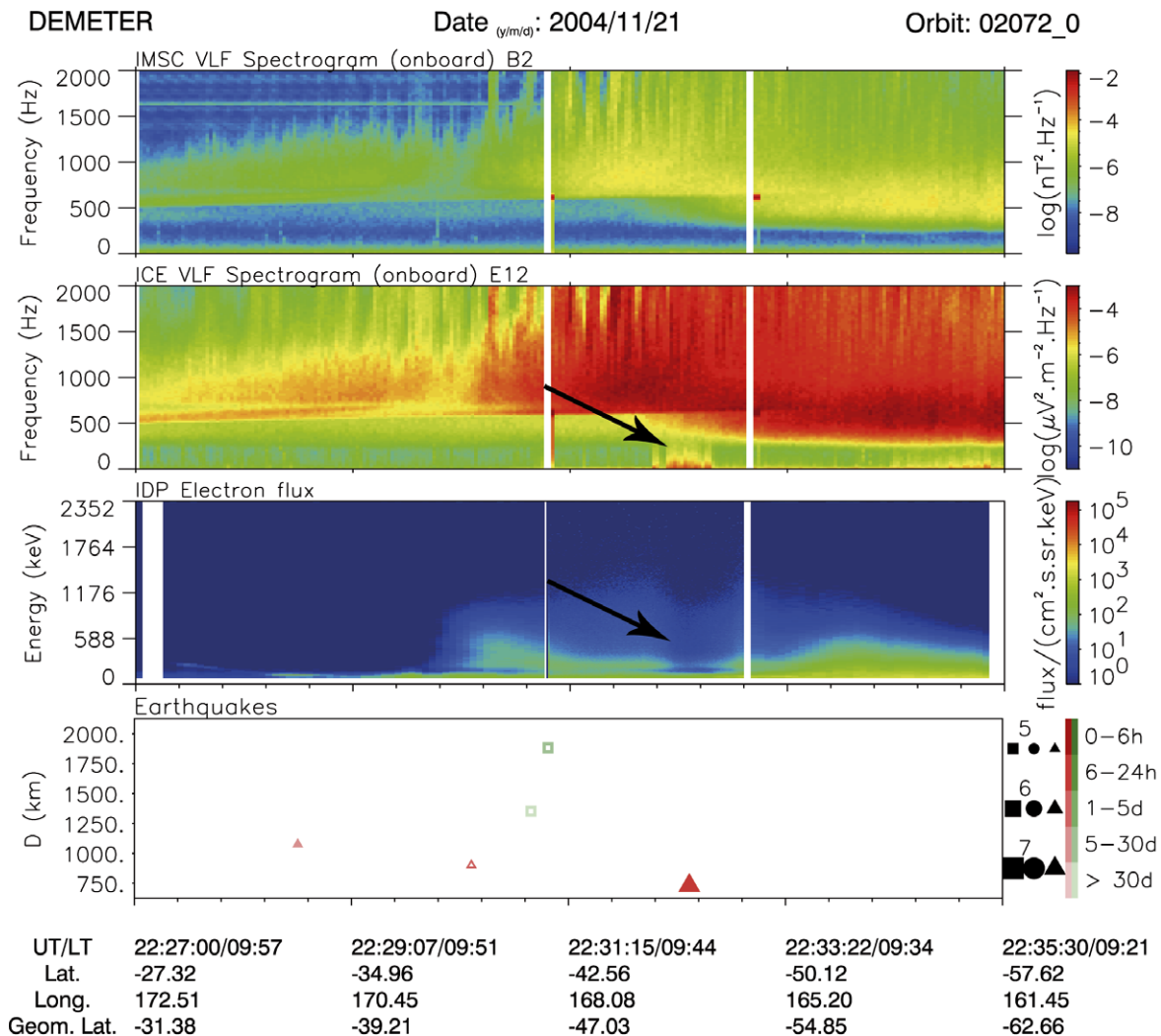


Fig. 11. Same as Fig. 9 but for the orbit which is shown in Fig. 10. The data is recorded 1 day before the earthquake indicated by a bright red triangle. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

of them have characteristics uniquely related with seismic activity.

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